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Effect of Joint Clearances on the Accuracy of TCP Trajectory of Robot Manipulator

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Abstract*: In this study, the effect of joint clearances on the accuracy of the Tool Centre Point's trajectory of a serial robot manipulator is investigated. CAD models of a serial manipulator is prepared, having different values of the clearance at the joints. The TCP trajectory is obtained by running simulations for all the models, under the same set of constraints and forces. The trajectory is compared with that of a model with perfect joints and the effect on accuracy is examined. The results explicitly confirm that the clearance at the joints effects the accuracy of the trajectory of the TCP. It is also concluded that larger clearance leads to larger errors and the error accumulate over time and can adversely affect the performance of the robot manipulators.

***Keywords*: Joint Clearance, Robot Manipulator, Robot Welding, Trajectory, Tool Centre Point, Accuracy**

I. INTRODUCTION

As the manufacturing technology is rapidly evolving, robots are being used in industrial applications where high degree of accuracy, precision and stability of operations are required. Robotic manipulators are employed to perform a wide variety of operations such as arc welding, part handling, painting, assembly, and also in packaging. Robotic manipulators not only improve the production efficiency and working conditions but also help in the automation of industries. The most common type of robotic manipulator used in the industry today are serial manipulators, due to their large workspace size, smaller footprint, and versatile applications. They are designed as a series of rigid links connected by motor-actuated joints that extend from a base to an end-effector. They usually have 6 joints, 1 fixed and 5 revolute, so as to have 6 degrees of freedom to place a manipulated object in any arbitrary position and in any orientation in the workspace of the robot. In the general performance analysis of the robot manipulator systems, each of the revolute joint is assumed as ideal or perfect without any clearance. But in any real system, factors such as wear due to friction, cost of accuracy, manufacturing process limitations make the clearance unavoidable. The clearances in joints always exist due to the assembly errors, manufacturing errors and wear. Moreover, such clearance is necessary to allow for relative motion between the connected arms of the robots and to permit the assembly of components as well. The clearance occurs in each active joint where movement is desired. The unavoidable existence of clearance in joints leads to impact dynamic loads at the joints, vibrations, random errors and also affects the transfer of the system load which may lead to the destruction and failure of the entire system. The movements of the real system varies from the ideal one and the accuracy of the manipulator trajectory is decreased due to joint clearances. In precision engineering, it is imperative to of predict the accuracy of the system for obtaining better results.

Over the last few years the constant need for accurate and efficient systems has led to various theoretical and experimental investigations being conducted to determine the dynamic and kinematic effects of spatial robotic manipulator systems having joint clearances. Subudhi and Morris [1] 2002, have presented dynamic modelling, simulation and control of a manipulator with flexible links and joints. The general model formulation can be exploited to obtain the closed-form dynamic models for practical flexible manipulators with any number of links. However, the joints of robot manipulator were considered perfect, and there was no consideration on the clearance at the joints. Zhu and Ting [2] 2000 presented a probability density function to investigate the performance uncertainty caused by the joint clearance in a robot manipulator. Based on the general p.d.f. of the endpoint, the distribution functions of the robot endpoint for any position tolerance zone and any joint distribution type, can be derived. Jia et al. [3] 2002, have presented theoretical and experimental studies about dynamic behaviour of a planar mechanism of slider-crank type with clearance. Effects of different clearance size and driving speed are investigated both theoretically and experimentally. Flores et al. [4-7] investigated the joint clearances effect on kinematics and dynamics of planar and spatial slider-crank mechanisms with elastic, rigid links. Different clearance sizes and joint types were analysed. Khemili and Romdhane [8] 2008, have investigated the dynamic behaviour of a planar flexible slider–crank mechanism having joint with clearance. Simulation and experimental tests are carried out for this goal. The results show the change in the slider acceleration, the impact forces and the torque acting on the crank are effected by clearances. Brutti et. al. [9] 2011, have presented a general computer-aided model of a 3D revolute joint with clearance by introducing a nonlinear equivalent force system, which considered the contact elastic deformations. The proposed model allows to improve the accuracy in the evaluation of the dynamic behaviour of an industrial mechanism. Zhao and Bai [10] 2011, have investigated dynamics of a space robot manipulator with joint clearance. The nonlinear equivalent spring-damper model was established for the contact model in joint clearance. Also, the friction effect was considered using the Coulomb friction model. Erkaya [11] 2012, has investigated the effect of joint clearance on the degrees of freedom, where one out of six joints as imperfect. It was concluded that higher size of joint clearance causes additional freedom and increases the amplitudes of accelerations and joint forces. However, in the above simulation experiments, due to computational limitations, only one joint was considered as imperfect. This study, focusses on the effect of joint clearance on the accuracy of TCP trajectory of a robot manipulator, when the clearance is present at all of the joints having relative motion between the connected members.

It was established earlier that even with an accurate design and using best manufacturing process, joint clearances cannot be completely eliminated. Even with the smallest clearance sizes the kinematic and dynamic outputs of the system such as trajectory, torques etc. are effected. This paper investigates the effects of joint clearances on the accuracy of the trajectory of the end effector of a robot manipulator system. To achieve this goal, this paper is organized into 4 sections; in Section 2, the models of robotic manipulator system is prepared with different clearances at all the joints, the constraints of the system are defined, and the motor drivers are initialised. The simulation results and discussions are briefly summarized in Sections 3 and 4 respectively.

II. MODEL OF ROBOTIC MANIPULATOR

The most common type of robotic manipulator used in industry today are serial manipulators. They have a series of rigid links connected by motor-actuated joints that extend from a base to an end-effector. The 6 arm robot usually has 6 joints, 1 fixed and 5 revolute, so as to have 6 degrees of freedom to perform operations on a manipulated object in any arbitrary position and in any orientation in the workspace of the robot. The base of the robot manipulator is fixed to the ground. The last link or arm is known as the end effector. At this endpoint the tools are attached. In a wider sense, an end effector can be seen as the part of a robot that interacts with the work environment. The tip of the end effector is known as the Tool Centre Point (TCP). The robot's position in space is defined using the TCP.

For the present analysis, a six-axis industrial robot is considered. It has 5 revolute joints and one fixed joint. The main applications of this robot are handling, welding, assembly etc. The robot is shown in Fig. 1. The centre of the face of the end-effector is defined as the TCP of the robot and its trajectory is tracked as a part of the accuracy analysis. Initially all the joints are designed to be perfect i.e. no clearance exists at the joints.

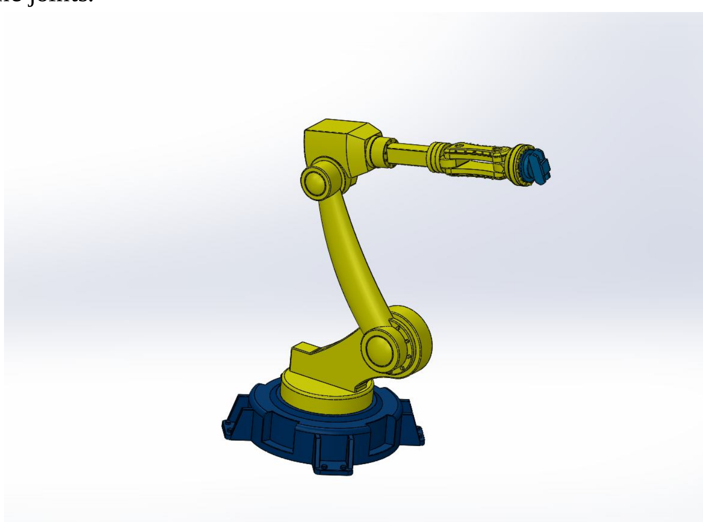

Fig. 1. 3D Model of Robot Manipulator

In the typical analysis of the revolute joints, the centres of the journal and bearings coincide i.e. the joint is considered as ideal or perfect. However when clearance is present in the joint, the two centres do not coincide making the joint imperfect. Practically, the clearances in joints are unavoidable due to the assembly errors, manufacturing errors and wear. The clearance is necessary for assembly of the members or for any kind of relative motion between the connected members. When the clearance exists, two kinematic constraints of the joint are eliminated and two additional degrees of freedom are added to the system viz. vertical and

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horizontal displacements of the journal with respect to the bearing. As shown in Fig. 2, the radial clearance in a joint is the difference between the radii of the journal and the bearing. Fig. 2 illustrates a revolute joint with clearance in a mechanical system. The bearing is part of body b and the journal is part of body *j*.

The radial clearance, C_r, is expressed as,

$$C_r = R_b - R_j$$

Similarly the diametrical clearance C_d is expressed as

$$C_d = D_b - D_j$$

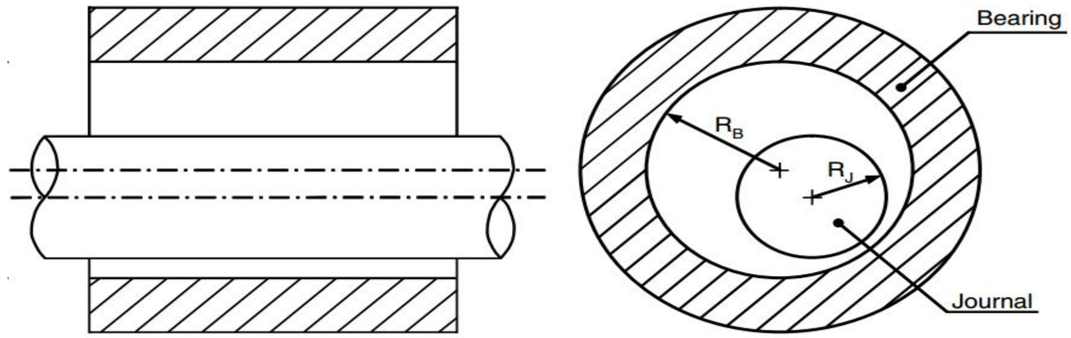

Fig. 2. Revolute joint with clearance. (Clearance is exaggerated for illustration)

To investigate the effect of joint clearances on the trajectory of TCP of the robot manipulator, five more CAD models are made each having different diametrical clearance values at each joint. The clearance sizes being considered by this paper are 0.001mm, 0.005mm, 0.01mm, 0.025mm and 0.05mm. In each model, all the joints are designed so as to have the same clearance. The geometric and mass characteristics of each arm in given in Table 1.The other parameters used to define the model are material dependent. The standard values are assigned to each parameter and are outlined in Table 2.

TABLE I

GEOMETRIC AND MASS PROPERTIES OF ROBOT MANIPULATOR

Robot Arms	Mass (in grams)	Central Distance (in mm)
Arm 1	18516	219
Arm 2	7199	322
Arm 3	10841	252
Arm 4	4009	195
End Effector	564	40

TABLE II

PARAMETERS IN DYNAMIC SIMULATION OF ROBOT MANIPULATOR

Description	Value
Material	Plain Carbon Steel
Dynamic Friction Coefficient	0.25
Stiffness	100 kN/mm
Maximum Damping	50 N-s/mm
Penetration	0.1mm
Integration step size	1×10^{-5} s
Simulation Accuracy	1×10^{-4} mm

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III.SIMULATION RESULTS

To impart motion, motors are defined at each of the five revolute joints. To ensure that the different geometrical or mass characteristics of the arms don't induce any idiosyncrasy, all the motors are programmed to run at the same speed of 0.5 RPM. All the six versions of the CAD models having different clearance sizes are simulated for 20 seconds and the software traces the motion plot of the TCP on the simulation space, as shown in Fig. 3. The curve is isolated and plotted as shown in Fig. 4.

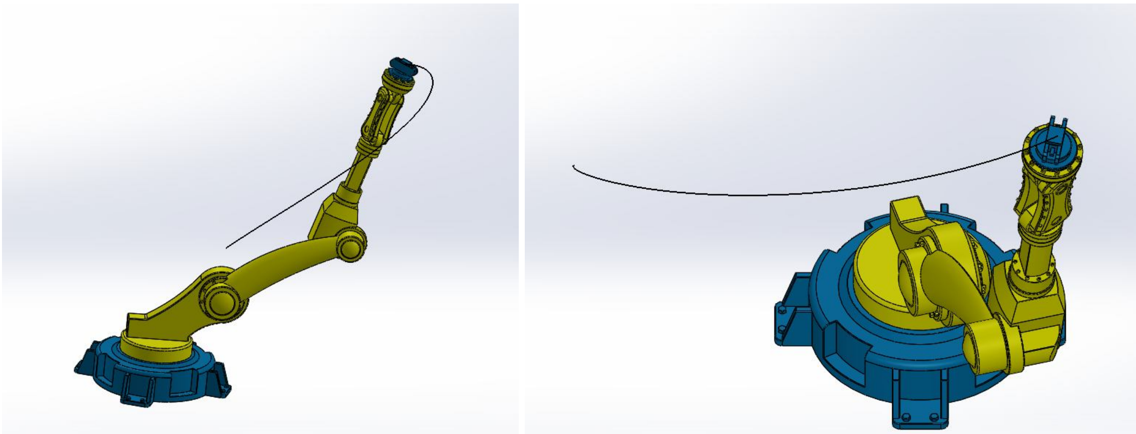

Fig. 3. Simulated Trajectory of the TCP

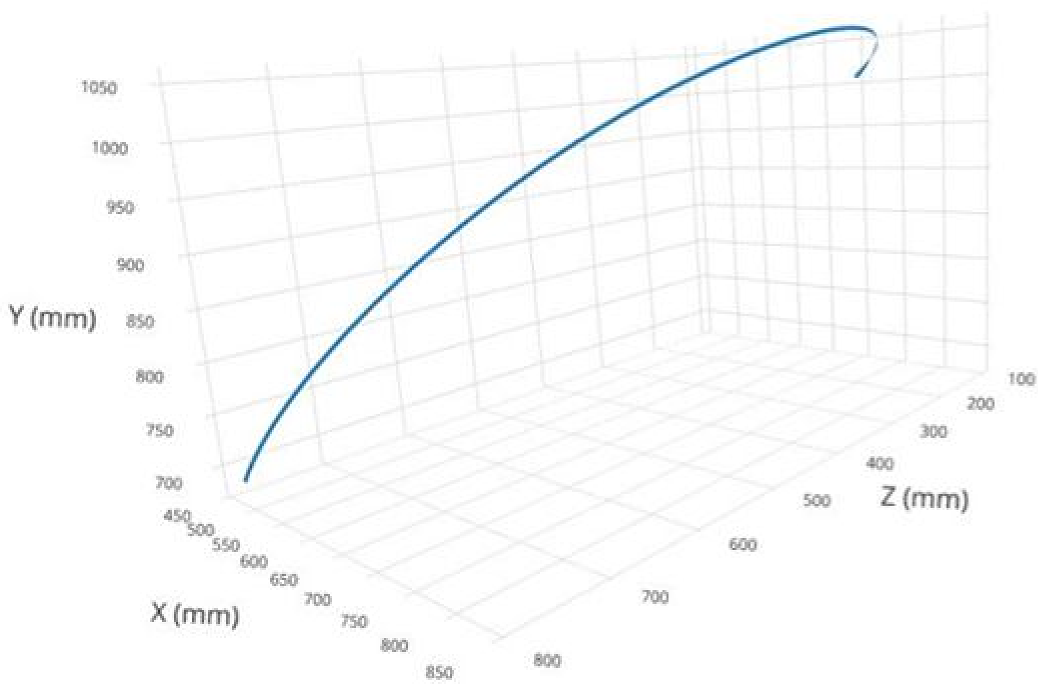

Fig. 4. Trajectory Curve

The TCP trajectory is isolated and represented by three dimensional coordinate points recorded continuously with an interval of 0.1 second between the points. The trajectory all six models are obtained and compared for error and deviation with the trajectory of TCP of the model with perfect joints. The error in the TCP position for all the five different clearance values at the joints is calculated with respect to the TCP of the model with no clearance and a graph of error vs. time is plotted. The error along X-coordinate of the models with imperfect joints are shown in Fig. 5(a), the error along Y-coordinate is shown in Fig. 5(b) and the error along Z-coordinate is represented by Fig. 5(c). The spatial distance error is shown in Fig. 5(d).

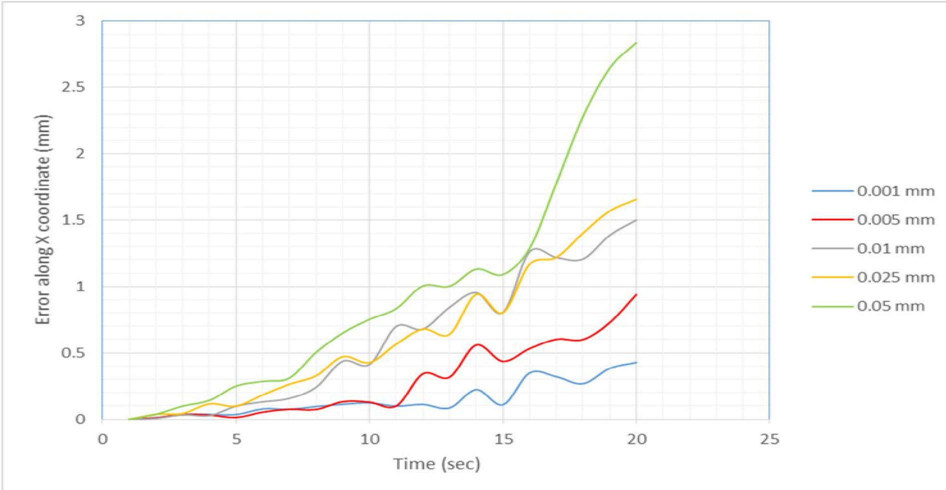

Fig. 5 (a)

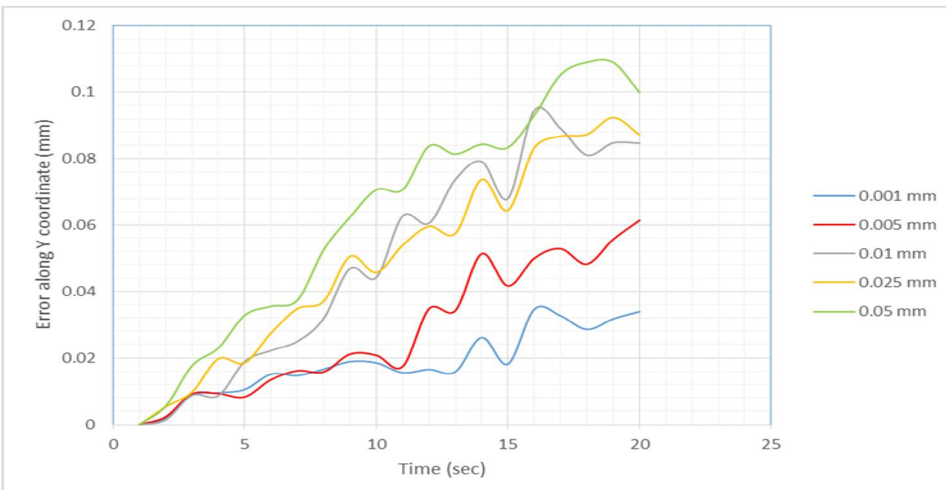

Fig. 5 (b)

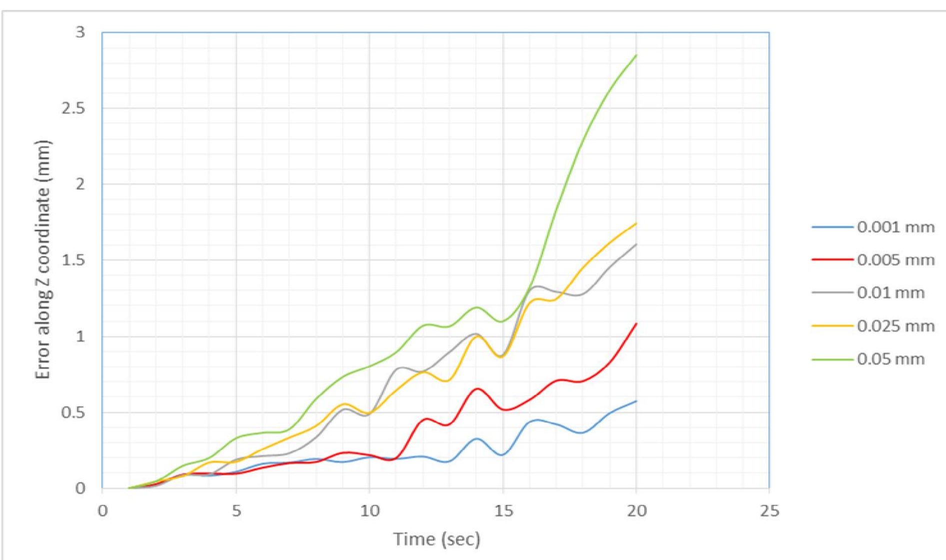

Fig. 5 (c)

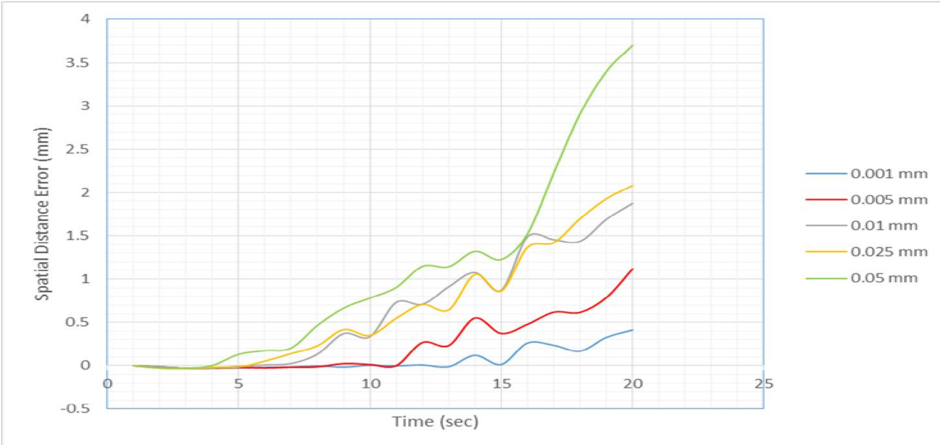

Fig. 5 (d)

Fig. 5. Errors in trajectory of different clearance values v/s time (the legend indicates the different values of clearance); (a) Error along X direction; (b) Error along Y direction; (c) Error along Z direction; (d) Spatial Distance Error

From the graphs it is observed that the accuracy of the trajectory of TCP is effected by the presence of clearance at the joints. It is also notable that as the value of clearance increases the accuracy of the trajectory decreases. It can be seen that over time the errors accumulate and result in reduced accuracy of the trajectory and increased error.

IV. DISCUSSION & CONCLUSION

As precision and accuracy is a highly sought after quality in industrial robots, the aim of this study was focussed on studying the effects of joint clearances on the accuracy of the TCP trajectory of a serial robot manipulator. The manipulator has six degrees of freedom and five revolute joints. In the current study all the joints are considered to be imperfect and have five different clearance values. The simulation was conducted on all the six CAD models and the results were obtained and analysed.

The results explicitly confirm that the clearance at the joints effects the accuracy of the trajectory of the TCP. From the evaluation of the results, it is concluded that larger clearance leads to larger errors. Also, the errors are accumulated over time and amplified from arm to arm. This causes the accuracy of TCP trajectory to increasingly diminish over time. It must be noted that even for a manipulator having clearance as small as 0.05 mm, the end position of TCP is as far as 3.7 mm away from the end position of a manipulator with perfect joints. This emphasises the need to minimise the clearance at the joints to as low as possible and also accommodate the possible corrections into the robot control system. As clearance is practically unavoidable and, having confirmed the effect of clearance on the accuracy and the magnitude of error being considerable, it is imperative to design a robust control system for generating the necessary control outputs. The future scope of this study could be to develop an equation that establishes the error in the TCP trajectory as a function of clearance and time.

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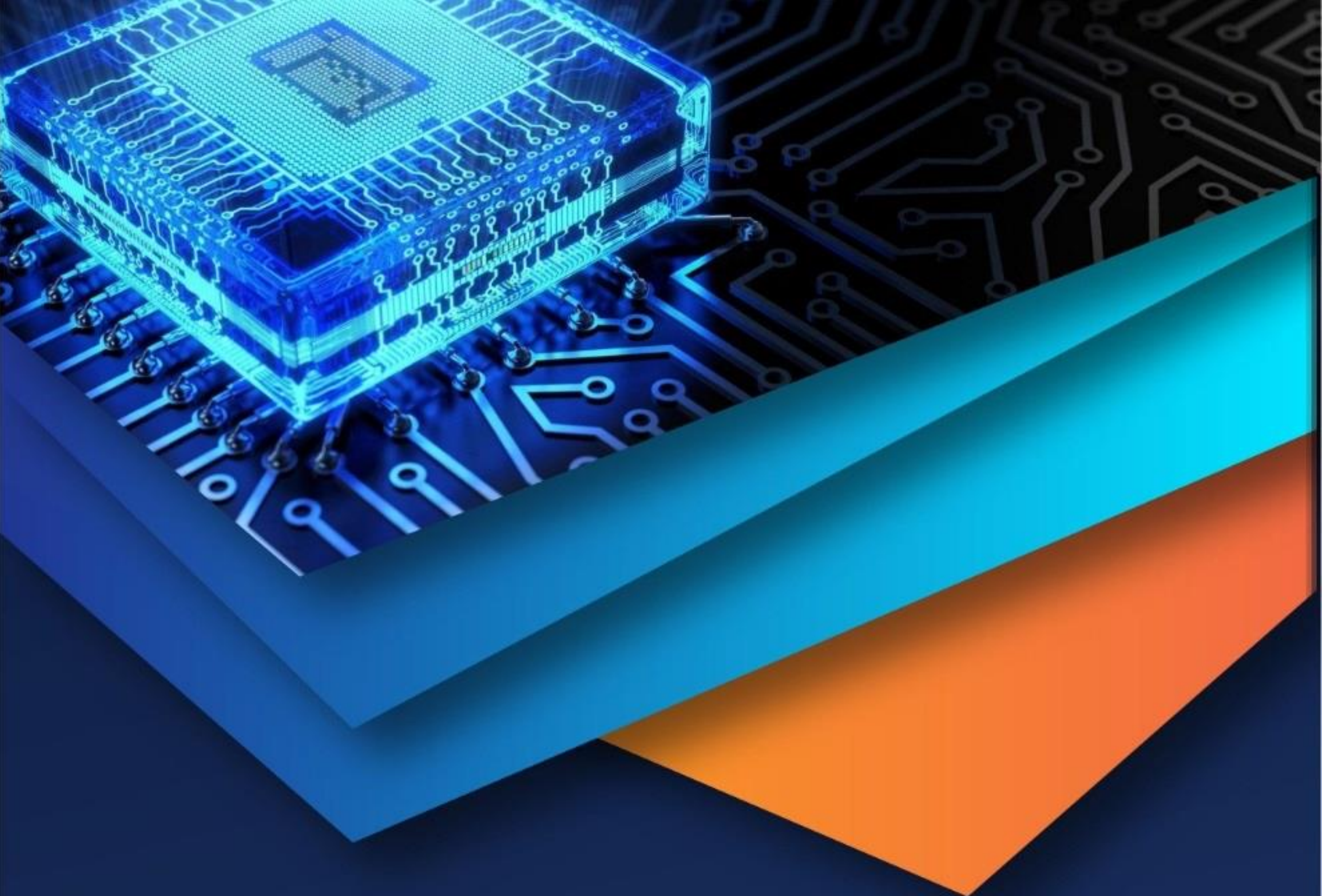

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